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EXPERT CONTROL SYSTEM FOR COAL BLENDING PROCESS IN AN IRON AND STEEL CORPORATION①

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ABSTRACT Based on the statistical data and experience knowledge of the coal-blending and coking process, a mathematical model and rule model which forecast the quality of coke and compute blending ratio of coal (BRC) were presented. An algorithm to compute BRC was provided by combining the two models mentioned above. A two-level expert control system (ECS) composed of industrial computers and a Honeywell S9000e controller was designed to calculate BRC and control the coal-blending process, which can not only guarantee the precision of calculating BRC but also make the actual BRC follow the target BRC. The accuracy of coal blending and the prediction precision of coke quality have been come up to 97 % and 95 % respectively.

Key words coal-blending process blending ratio of coal expert control mathematical model rule model

1 INTRODUCTION

As a kind of intelligent method, expert control can deal with all kinds of quantitative or qualitative, precise or fuzzy information by combining perceptual experience with algorithms. It can flexibly correct control strategies and parameters according to on-line information to achieve good performance[1,2]. Since expert control was proposed by Åström[3], people have paid close attention to it. Progresses in its theory and application have been made[4]. Recently, some expert control systems were applied in complicated process in nonferrous metals industry successfully[5,6]. But how to improve performance of expert control system effectively to a practical object in industry is still a difficult problem which needs further study.

In iron and steel industry, the quality of iron produced in blast furnace is directly influenced by the quality of coke, while the quality of coke depends on the quality of blended coal. In coal-blending process different kinds of coal are blended with each other in a proper ratio to form blended coal before it is sent to coke oven to make coke. This is a complex industrial process influenced by many factors, in which many physical and chemical changes have occurred. So, it is very difficult to describe the relationship among the quality of coke, blended coal and each kind of coal[7]. In the past, the blending ratio of coal (BRC) is determined by engineers according to qualities of each kind of coal, production environment and experience, etc. Because there are too many kinds of coal and the composition of coal may change, it is very difficult and imprecise to calculate BRC manually. Even though BRC is worked out, the quality of blended coal can not be guaranteed as a result of imprecision of blending coal manually. Therefore, based on the characteristics and experience knowledge of coal-blending and coking process, an expert control system is designed to control the coal-blending process which calculates BRC, forecasts the quality of coke and controls the flow of coal.

2 STRUCTURE OF ECS

In an iron and steel corporation there are seven coal buckets. Each kind of coal is sent from coal field and conveyed to belt 0, then put into a coal bucket. When a disc feeder is started, coal in bucket is conveyed to belt 1 by rotation of

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disc. Coal is blended evenly by the crasher and return belt, and then sent to coke oven. In the past, operators controlled the flow of each kind of coal through regulating positions of thimbles and dampers manually. The production process of blending coal is showed in Fig.1.

A two-level expert control system composed of expert system and distribution control system (DCS) is constructed. The expert system, based on the process and experience knowledge, calculates BRC of each kind of coal as target value to DCS according to quality indices of coke and each kind of coal. DCS is composed of a monitoring computer, frequency converters, belt balances, and S9000e controller with modules such as A/D converters, D/A converters, digital input modules (DI), and digital output modules (DO). As the upper-computer of S9000e controller, the monitoring computer is in charge of program configuration, adjustment of control parameters, display of running states, and communication with the expert computer. The S9000e controller implements control of flow of coal, which should follow the target value that is worked out by the upper-computer. The structure of expert contrll system (ECS) is shown in Fig.2.

3 CALCULATION OF BRC

Calculation of BRC is to properly select the blending ratio of each kind of coal to improve the efficiency of blending coal on condition that the quality of coke is guaranteed. The relationship between BRC and the quality of coke can not be described with single mathematical model, so a method on combining mathematical model with a rule model is presented to seek proper BRC.

3.1 Prediction model of coke quality

The effect of making iron in blast furnace is directly influenced by breakage-resisting M_{40}, wearability-resisting M_{10}, sulfur content S^g_Q and ash content A^g of coke, and the cohesive index G, volatilization content V^r_p, sulfur content S^g_{Qp} and ash content A^g_p of the blended coal influence the quality of coke[8]. Since the blended coal is made from many kinds of coal, its quality indices are determined by the quality indices and BRC of each kind of coal. Two steps are taken to forecast the quality of coke: at first the quality of blended coal is forecasted with the quality indices of every kind of coal in bucket, then the quality of coke is forecasted with the quality of blended coal.

3.1.1 Prediction of blended coal quality

Only physical changes occur in coal-blending process, so the quality of blended coal can be forecasted by weighed computing quality indices and BRC of each kind of coal.

Fig.1 Process of coal-blending

Fig.2 Structure of ECS

FC—Frequency converter; CCP—Coal-blending and coking process

If the blended coal is composed of N kinds of coal, X_i is the BRC of kind i, and let its cohesive index be G_i, volatilization content V_{di}, sulfur content S^g_{Qdi}, ash content A^g_{di}, the quality indices of the blended coal can be calculated as

$$G = \sum_{i=1}^{N} X_i G_i + \Delta G \tag{1a}$$

$$V^r_p = \sum_{i=1}^{N} X_i V^r_{di} + \Delta V \tag{1b}$$

$$S^g_{Qp} = \sum_{i=1}^{N} X_i S^g_{Qdi} + \Delta S \tag{1c}$$

$$A^g_p = \sum_{i=1}^{N} X_i A^g_{di} + \Delta A \tag{1d}$$

where ΔG, ΔV, ΔS and ΔA are experience rectifying values of cohesive index, volatilization content, sulfur content and ash content respectively. Let

$$\boldsymbol{D} = \begin{bmatrix} G_1 & G_2 & \cdots & G_N \\ V^r_{d1} & V^r_{d2} & \cdots & V^r_{dN} \\ S^g_{Qd1} & S^g_{Qd2} & \cdots & S^g_{QdN} \\ A^g_{d1} & A^g_{d2} & \cdots & A^g_{dN} \end{bmatrix}$$

$$\boldsymbol{X} = \begin{bmatrix} x_1 \\ x_2 \\ \cdots \\ x_N \end{bmatrix} \quad \boldsymbol{P} = \begin{bmatrix} G \\ V^r_p \\ S^g_{Qp} \\ A^g_p \end{bmatrix} \quad \Delta \boldsymbol{P} = \begin{bmatrix} \Delta G \\ \Delta V \\ \Delta S \\ \Delta A \end{bmatrix}$$

Equation (1) can be expressed as

$$\boldsymbol{P} = \boldsymbol{D}\boldsymbol{X} + \Delta \boldsymbol{P} \tag{2}$$

The forecasting error of times $k+1$ is defined as the subtraction of the forecasting value $\boldsymbol{P}(k)$ and the actual value $\boldsymbol{P}_A(k)$ of times k just as following:

$$\Delta \boldsymbol{P}(k+1) = \boldsymbol{P}(k) - \boldsymbol{P}_A(k) \tag{3}$$

A set of experience rectifying values ΔG, ΔV, ΔS and ΔA is selected to form $\Delta P(1)$ at first, so the model to forecast the quality of blended coal is obtained:

$$\Delta \boldsymbol{P}(k+1) = \sum_{n=1}^{k} [\boldsymbol{D}(n)\boldsymbol{X}(n) - \boldsymbol{P}_A(n)] + \Delta \boldsymbol{P}(1) \tag{4a}$$

$$\boldsymbol{P}(k+1) = \boldsymbol{D}(k+1)\boldsymbol{X}(k+1) + \Delta \boldsymbol{P}(k+1) \tag{4b}$$

3.1.2 Prediction of coke quality

Ash is inert and remains complete, and sulfur is decomposed, about 25 % ~ 35 % of which runs out during the coking process, so we can get

$$A^g = \frac{1}{\eta_c} A^g_p + \Delta A^g \tag{5a}$$

$$S^g_Q = \frac{\eta_s}{\eta_c} S^g_{Qp} + \Delta S^g_Q \tag{5b}$$

where $\eta_c = 0.75 \sim 0.80$ is coking rate, $\eta_s = 0.65 \sim 0.75$ is sulfur residual rate, ΔA^g and ΔS^g_Q are rectifying value of ash and sulfur content whose solutions are derived as same as $\Delta \boldsymbol{P}$.

The main factors which influence M_{40} and M_{10} are such quality indices of the blended coal as G, V_p^r and A_p^g. By using of statistical data of the production process, the relationship can be gotten with linear regression method.

$$M_{40} = a_0 + a_1 G + a_2 V_p^r + a_3 A_p^g \quad (6a)$$

$$M_{10} = b_0 + b_1 G + b_2 V_p^r + b_3 A_p^g \quad (6b)$$

where a_i and $b_i (i = 0, 1, 2, 3)$ are regressive factors. Let

$$y = [M_{40} \quad M_{10}]$$

$$z = [1 \quad G \quad V_p^r \quad A_p^g]$$

$$\theta = \begin{bmatrix} a_0 & b_0 \\ a_1 & b_1 \\ a_2 & b_2 \\ a_3 & b_3 \end{bmatrix}$$

Then Eqn.(6) can be simplified as:

$$y = z\theta \quad (7)$$

If n independent groups of data are selected from statistical data of the process as sampled data,

$$Z(n) = \begin{bmatrix} z(1) \\ z(2) \\ \vdots \\ z(n) \end{bmatrix} = \begin{bmatrix} 1 & G(1) & V_p^r(1) & A_p^r(1) \\ 1 & G(2) & V_p^r(2) & A_p^r(2) \\ \vdots & \vdots & \vdots & \vdots \\ 1 & G(n) & V_p^r(n) & A_p^r(n) \end{bmatrix}$$

$$Y(n) = \begin{bmatrix} y(1) \\ y(2) \\ \vdots \\ y(n) \end{bmatrix}$$

And let J be an objective function shown in Eqn.(8), the estimated value $\hat{\theta}(n)$ of least mean square of $\theta(n)$ is found from Eqn.(9):

$$J(n) = \sum_{i=1}^{n}[y(i) - z(i)\theta][y(i) - z(i)\theta]^T \quad (8)$$

$$\hat{\theta}(n) = [Z^T(n) Z(n)]^{-1} Z^T(n) Y(n) \quad (9)$$

The coking environment, kinds of coal and quality of each kind of coal will change with time. Therefore the mathematical model which forecasts the quality of coke is rectified by on-line information to guarantee precision of the prediction model. That is to say, ΔA^g and ΔS_Q^g in Eqn.(5), $\hat{\theta}(n)$ in Eqn.(9) are rectified on-line.

3.2 Calculation of BRC

BRC is calculated according to the given quality indices of coke and each kind of coal. Because the quality indices of coke are described with a set of inequalities, the rule model to calculate BRC is established firstly.

3.2.1 Rule model

Aimed at the characteristics of coal-blending and coking process, a rule model to calculate BRC can be established by production rules in form of "IF conditions THEN results". In these rules, the conditions are ordinarily consisted of running states, and the results are the strategies to compute BRC. The main rules include:

R^1: IF M_{40} is less than M_{40G} OR M_{10} is greater than M_{10G} THEN G is increased AND V_p^r is decreased

R^2: IF M_{40} is much greater than M_{40G} OR M_{10} is much greater than M_{10G} THEN G is decreased AND V_p^r is increased

R^3: IF G is less than G_G AND G_i is greater than G_G THEN X_i is increased

R^4: IF G is less than G_G AND G_i is lower than G_G THEN X_i is decreased

R^5: IF G is much greater than G_G AND G_i is greater than G_G THEN X_i is decreased

R^6: IF G is much greater than G_G AND G_i is less than G_G THEN X_i is increased

R^7: IF V_p^r is greater than V_{pG}^r AND V_{di}^r is greater than V_{pG}^r THEN X_i is decreased

R^8: IF V_p^r is greater than V_{pG}^r AND V_{di}^r is less than V_{pG}^r THEN X_i is increased

R^9: IF S_{Qp}^g is greater than S_{QpG}^g AND S_{Qdi}^g is greater than S_{QpG}^g THEN X_i is decreased

R^{10}: IF S_{Qp}^g is greater than S_{QpG}^g AND S_{Qdi}^g is less than S_{QpG}^g THEN X_i is increased

R^{11}: IF A_p^g is greater than A_{pG}^g AND A_{di}^g is greater than A_{pG}^g THEN X_i is decreased

R^{12}: IF A_p^g is greater than A_{pG}^g AND A_{di}^g is less than A_{pG}^g THEN X_i is increased

In the rules, M_{40G}, M_{10G}, G_G, V_{pG}^r, S_{QpG}^g and A_{pG}^g are given indices.

3.2.2 Algorithm of BRC

The expert system computes BRC by means of prediction model and rule model. At first the quality index of the blended coal is determined according to the given quality index of coke, then BRC is computed according to the quality index of blended coal.

Let M_{40G}, M_{10G}, S^g_{QG} and A^g_G be the given qualitative indices of coke, the given quality indices G_G, V^r_{pG}, S^g_{QpG} and A^g_{pG} of the blended coal are to be found to make the quality of coke satisfy the following formulae:

$$M_{40} \geqslant M_{40G} \quad (10a)$$

$$M_{10} \leqslant M_{10G} \quad (10b)$$

$$S^g_Q \leqslant S^g_{QG} \quad (10c)$$

$$A^g \leqslant A^g_G \quad (10c)$$

The method to determine the quality indices of blended coal includes several steps. Firstly a set of experience value of the quality indices of blended coal is chosen as initial value. Secondly M_{40}, M_{10}, S^g_Q, and A^g of coke are computed according to Eqn.(5) and (7). If the indices of coke can not satisfy formula (10), the quality indices of blended coal are to be regulated until the quality indices of coke satisfy formula (10). The regulating algorithm is

$$G_G = G_G + \Delta G_G \quad (11a)$$

$$V^r_{pG} = V^r_{pG} + \Delta V^r_{pG} \quad (11b)$$

If such indices satisfy the condition in rule R^1, the regulating amounts of G_G and V^r_{pG} are computed by

$$\Delta G_{M1} = k_{M1}\frac{M_{40G} - M_{40}}{\hat{a}_1 L} + k_{M2}\frac{M_{10G} - M_{10}}{\hat{b}_1 L}$$

$$\Delta V_{M1} = k_{V1}\frac{M_{40G} - M_{40}}{\hat{a}_2 L} + k_{V2}\frac{M_{10G} - M_{10}}{\hat{b}_2 L}$$

If such indices satisfy the condition in rule R^2, the regulating amounts of G_G and V^r_{pG} are computed by

$$\Delta G_{M2} = k_{M3}\frac{M_{40G} + M_{M40} - M_{40}}{\hat{a}_1 L} + k_{M4}\frac{M_{10G} + M_{M10} - M_{10}}{\hat{b}_1 L}$$

$$\Delta V_{M2} = k_{V3}\frac{M_{40G} + M_{M40} - M_{40}}{\hat{a}_2 L} + k_{V4}\frac{M_{10G} + M_{M10} - M_{10}}{\hat{b}_2 L}$$

So regulating amounts ΔG_G and ΔV^r_{pG} are calculated by

$$\Delta G_G = \Delta G_{M1} + \Delta G_{M2} \quad (12a)$$

$$\Delta V^r_{pG} = \Delta V_{M1} + \Delta V_{M2} \quad (12b)$$

where L is the computing step length whose value influences the calculation convergence, k_{Mi} and k_{Vi} (i = 1, 2, 3, 4) are the experience rectifying coefficients, M_{M40} is the subtraction of M_{40G} and the maximum permitted value of M_{40}, M_{M10} is the substration of M_{10G} and the minimum permitted value of M_{10}.

The method to determine BRC by the quality of blended coal includes several steps. At first, an experience value of BRC is selected as initial value; then G, V^r_p, S^g_{Qp}, and A^g_p of the blended coal are computed with Eqn.(4); and these indices are judged by the conditions in rules R^3 ~ R^{12}. If some conditions are satisfied, the BRC will be rectified according to the corresponding rule; if not, the calculated BRC is used to check whether such quality index of the blended coal can be reached. The rectifying algorithm is given by

$$X_i = X_i + \Delta X_i \quad (13a)$$

$$\Delta X_i = \frac{G_G - G}{L_x \times \mathrm{sgn}(G_i - G) \times \sum_{i=1}^{N} G_i} \quad (13a)$$

where ΔX_i is the rectifying value, L_x is the rectifying step length and sgn( ) is a signal function whose result is 1 or -1.

4 DESIGN OF DCS

DCS realizes automation of the coal-blending process. Its monitoring computer receives the target value of BRC from the expert system as given value. Seven PI control loops are applied to control the flow of coal from seven coal buckets whose main tasks are restraining disturbance.

$$U_i(k) = \begin{cases} U_i(k-1) & |e_i(k)| \leqslant \varepsilon \\ U_i(k-1) + K_{pi}[e_i(k) - e_i(k-1)] + K_{Ii}e_i(k) & |e_i(k)| > \varepsilon \end{cases} \quad (14)$$

where $i = 1, 2, \cdots, 7$; ε is the dead zone, which is 0.3 t/h; K_p and K_I are the proportional and integral coefficients of the controller, which are 0.4 and 0.3. The regulating period is 2 seconds. The digital control signal $U_i(k)$ is converted by D/A module to voltage between 0 ~ 10 V, and sent to a frequency converter to control the rotational speed of the disc motor. Then the feeding volume of coal is changed and the volume of each kind of coal is regulated to match the given value.

DCS conducts automatic start and stop of the disc feeders, real-time display for the height of coal in the bucket, real-time alarm for malfunctions, printing and displaying of historic trend curves and report tables. The height of coal can be calculated by Eqn.(15) without level transducers, which diminishes the working amounts of maintaining equipment.

$$\int_0^{T_0} v_0 \mathrm{d}t - \int_0^{T_i} v_i \mathrm{d}t - \pi(r_0 + kh_i)^2 h_i = 0 \qquad (15)$$

where h_i is the height of coal in bucket i, and r_0 is the bottom radius of the conical bucket, k is the conical gradient, v_0 and T_0 are the feeding speed and feeding time of belt 0 to bucket i, v_i and T_i are the feeding speed and feeding time of belt i.

5 APPLICATION EFFECTS

ECS has been put into practice since December 1994. The running results during these years have showed reliability, stable performance, and high precision of the system. Every performance index has been reached or been higher than required. Curve 1, 2 and 3 in Fig.3 are the historic trend curves in eight hours of flow of blending coal whose target value are 44.68 t/h, 35.72 t/h and 27.53 t/h. It is concluded that the disturbance can be restrained quickly in desired area and the precision of blending coal can reach 97 % from 65 % when blending manually. The forecasting precision of coke quality is higher than 95 % in which the maximum error of M_{40} and M_{10} is 2.8 %, and the minimum is 0.1 %; the maximum error of A^g is 4.3 %, and the minimum is 0.6 %; the maximum error of S^g_Q is 4.8 %, and the minimum is 3.1 %.

Fig.3 Historic trend curves in eight hours of flow of blending coal

The technique which combines analytic mathematical model with rule model can avoid establishing complex mathematical model and process all kinds of qualitative or quantitative, precise or fuzzy information. It is an important technique to realize control in complex industrial process. The running results have showed the effectiveness. The prediction model of coke quality, the calculation method of BRC, the control strategy for the flow of blending coal can be widely applied to coal-blending industry.

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